

Quantum secure direct communication based on order rearrangement of single photons

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Based on the ideal of order rearrangement and block transmission of photons, we present a quantum secure direct communication scheme using single photons. The security of the present scheme is ensured by quantum no-cloning theory and the secret transmitting order of photons. The present scheme is efficient in that all of the polarized photons are used to transmit the sender's secret message except those chosen for eavesdropping check. We also generalize this scheme to a multiparty controlled quantum secret direct communication scheme which the sender's secret message can only be recovered by the receiver under the permission of all the controllers.

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Quantum cryptography has been one of the most promising applications of quantum information science. It utilizes quantum effects to provide unconditionally secure information exchange. Since the first QKD protocol was proposed by Bennett and Brassard in 1984 [1], quantum key distribution (QKD) which provides unconditionally secure key exchange has progressed quickly. In recent years, a good many of other quantum cryptography schemes have also been proposed and pursued, such as quantum secret sharing (QSS)[2, 3, 4, 5, 6, 7], quantum secure direct communication (QSDC) [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. QSS is the generalization of classical secret sharing to quantum scenario and can share both classical and quantum messages among sharers. QSDC's object is to transmit the secret message directly without first establishing a key to encrypt them, which is different to QKD. QSDC can be used in some special environments which has been shown by Boström and Deng et al.[9, 10]. Many researches have been carried out in QSDC. We can divide these works into two types, one utilizes single photons [11, 12], the other utilizes entangled state [9, 10, 12, 13, 14, 15, 16, 17, 18, 19]. Deng et al. proposed a QSDC scheme using batches of single photons which serves as one-time pad [11]. Cai et al. presented a deterministic secure direct communication scheme using single qubit in a mixed state [12]. The QSDC scheme using entanglement state is certainly the mainstream. Boström and Felbinger proposed a "Ping-Pong" QSDC protocol which is quasi-secure for secure direct communication if perfect quantum channel is used [9]. Cai et al. pointed out that the "Ping-Pong" Protocol is vulnerable to denial of service attack or joint horse attack with invisible photon [20, 21]. They also presented an improved protocol which doubled the capacity of the "Ping-Pong" protocol [13]. Deng et al. put forward a two-step QSDC protocol using Einstein-Podolsky-Rosen

(EPR) pairs [10]. We presented a QSDC scheme using EPR pairs and teleportation [14] and a multiparty controlled QSDC scheme using Greenberger-Horne-Zeilinger states [15].

In Ref. [22], Deng et al. utilize controlled order rearrangement encryption to realize a QKD scheme. In their scheme, the communication parties share a control key used to control the order rearrangement operation. Very recently, A. D. Zhu et al. proposed a QSDC scheme based on secret transmitting order of entangled particles [23]. The security of their scheme is based on entanglement and the secret transmitting order of particles. In this Letter, we present a QSDC scheme using single photons based on the ideal of the order rearrangement and qubit transmission in batches [22, 23, 24]. The initial state of the transmitting photon is prepared randomly in one of the four states belonging to two conjugate basis, which is similar to the BB84 QKD protocol. The security of the scheme is based on quantum no-cloning theory and the secret transmitting order of single photons. All of the single photons are used to generate secret message except those used for eavesdropping check. It is not necessary for the communication parties to choose a random measuring basis for eavesdropping check. Compared with schemes using EPR pairs, this scheme is more realizable. We also generalize this scheme to a multiparty controlled quantum secret direct communication (MC-QSDC) scheme. In the MCQSDC scheme, the sender's secret message is transmitted directly to the receiver and can only be reconstructed by the receiver with the permission of all the controllers. We also discuss the security of the two schemes, which is unconditionally secure.

Here We first describe the details of our QSDC scheme using single photons. Suppose the sender Bob wants to transmit his secret message directly to the receiver Alice.

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(S1) Alice prepares N single photons each of which is

randomly in one of the following states

$$\begin{aligned} |H\rangle &= |0\rangle, \\ |V\rangle &= |1\rangle, \\ |+\rangle &= \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), \\ |-\rangle &= \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle). \end{aligned} \quad (1)$$

She then send the N photons $[P_1, P_2, \dots, P_n]$, called P -sequence to Bob.

(S2) Bob selects randomly a sufficiently large subset from the P -sequence for eavesdropping check, called checking sequence (C -sequence). The remaining photons of the P -sequence form a message sequence (M -sequence). Bob performs randomly one of the two unitary operations

$$\begin{aligned} I &= |0\rangle\langle 0| + |1\rangle\langle 1|, \\ U &= i\sigma_y = |0\rangle\langle 1| - |1\rangle\langle 0|. \end{aligned} \quad (2)$$

on each of the photons in the C -sequence. He also encode his secret message on the M -sequence by performing one of the unitary operations I and U , according to his secret message. If his secret message is “0” (“1”), Bob performs operation I (U). The operation U flips the state in both Z -basis ($|0\rangle, |1\rangle$) and X -basis ($|+\rangle, |-\rangle$), as

$$\begin{aligned} U|0\rangle &= -|1\rangle, U|1\rangle = |0\rangle, \\ U|+\rangle &= |-\rangle, U|-\rangle = -|+\rangle. \end{aligned} \quad (3)$$

(S3) Bob disturbs the order of the photons in the P -sequence and generates a rearranged photon sequence, called P' -sequence $[P'_1, P'_2, \dots, P'_n]$. He then sends the P' -sequence to Alice. The order of P' -sequence is completely secret to others but Bob himself, which ensures the security of the present scheme.

(S4) Alice tells Bob she has received the P' -sequence. After hearing from Alice, Bob announces the position of the C -sequence and the secret rearranged order in it. He also publishes his corresponding operations on the photons in the C -sequence.

(S5) Alice has the initial state information and the position of each checking photons. She then performs von Neumann measurement on each of the checking photons. If the initial state of the checking photon is $|H\rangle$ or $|V\rangle$ ($|+\rangle$ or $|-\rangle$), Alice performs Z -basis (X -basis) measurement on it. Alice has the initial states information of the checking photons, Bob's operation information on the checking photons and her measurement results on them. She can then evaluate the error rate of the transmission of the P -sequence. If the error rate exceeds the threshold, they abort the scheme. Otherwise, they continue to the next step.

(S6) Bob publishes the secret order of the M -sequence. According to the initial states information of the M -sequence, Alice performs Z -basis or X -basis measurement on the M -sequence. She can then obtain Bob's secret message.

We now discuss the unconditional security of the present scheme. The security of the scheme is based on quantum no-cloning theory and the secret transmitting order of the photons. Quantum no-cloning theory ensures that an eavesdropper, Eve cannot make certain the initial states of the transmitting photons prepared by Alice, which is similar to the BB84 QKD protocol. The difference between the BB84 QKD protocol and the present scheme is that the communication parties perform Z -basis or X -basis measurement randomly for preventing eavesdropping in the former, but the order rearrangement is used to prevent Eve from obtaining the sender's secret message in the latter. Suppose Eve intercepts the P -sequence and resends another photon sequence prepared by Eve to Bob. After Bob has performed his operations on the photon sequence, he then sends it to Alice. Eve can also intercepts this photon sequence. However, Eve cannot obtain Bob's operation information because Bob disturbs the order of the photon sequence and Eve's attack will be detected during the eavesdropping check. Without the correct order of the photon sequence, Eve can only obtain a batch of meaningless data. Obviously, the present scheme is also safe against collective attack due to the secret order of rearranged photon sequence. As we described above, the present scheme is unconditionally secure.

We then generalize this QSDC scheme to a MCQSDC scheme. Suppose the sender Bob wants to transmit his secret message directly to the receiver Alice under the control of the controllers Charlie, Dick, ..., York and Zach.

(S1') Alice prepares a batch of N single photons randomly in one of the four states $|H\rangle$, $|V\rangle$, $|+\rangle$, $|-\rangle$ and sends this batch of photons to Charlie.

(S2') Charlie performs randomly one of the three unitary operations I , U , H on each photon, where

$$H = \frac{1}{\sqrt{2}}(|0\rangle\langle 0| - |1\rangle\langle 1| + |0\rangle\langle 1| + |1\rangle\langle 0|) \quad (4)$$

is a Hadamada operation. H can realize the transformation between Z -basis and X -basis,

$$\begin{aligned} H|0\rangle &= |+\rangle, H|1\rangle = |-\rangle, \\ H|+\rangle &= |H\rangle, H|-\rangle = |V\rangle. \end{aligned} \quad (5)$$

He then sends the N photons to the next controller, say Dick. Dick and the remaining controllers repeat the similar operations as Charlie until Zach finishes his operations on the N photons. Zach then sends the N photons to Bob.

(S3') Similar to (S2), Bob encodes his random message and secret message on the C -sequence and M -sequence, respectively. He also disturbs the order of the P -sequence and send the rearranged P -sequence to Alice.

(S4') After hearing from Alice, Bob announces the C -sequence and the secret order in it. He then let Alice publish the initial states of the sampling photons. To prevent Alice's intercept-resend attack, for each of the

sampling photons Bob selects randomly a controller to announce his or her H operation information on the sampling photon firstly and then the others do in turn. That is to say, the controllers do not publish their I or U operation information but only publish their H operation information on the sampling photons. According to these information, Alice can measure the sampling photons in a correct measuring basis. She tells Bob his measurement results. Bob chooses randomly a controller to publish his or her I , U operation information on each of the sampling photons firstly and then the others do one by one. Thus Bob can determine the error rate of the transmission of the P sequence. If he confirms there is no eavesdropping, the process is continued. Otherwise, the process is stopped.

(S5') Bob publishes the secret order of the M -sequence. If the controllers permit Alice to reconstruct Bob's secret message, they tell Alice their operation information. Thus Alice can obtain Bob's secret message under the permission of the controllers Charlie, \dots , York, Zach.

The H operation performed by the controllers is very important for the security of the scheme. The nice feature of the H operation which can realize the transformation between Z -basis and X -basis can prevent Eve or a dishonest controller from obtaining the control information of the controllers. If the controllers only performs I or $i\sigma_y$ operations on the P sequence, Eve or a dishonest Alice can obtain the control information by taking intercept-resend attack. Eve intercepts the P -sequence and resends a fake photon sequence to the controller. After the controller has performed his or her operations on the P -sequence and sent it to the next controller, Eve can also intercept the photon sequence and then obtain the controller's information by measuring it. Bob firstly let the controllers publish their H operation information and then Alice can choose a correct measuring basis. Only after Alice has published her measurement results could the controllers announce their I , U operation information. It can prevent Alice from obtaining Bob's secret message without the control of the controllers. If the controllers publish all of their operation information firstly, Alice can break the control of the controllers by taking

intercept-resend attack. In this attack, she sends the P -sequence to Bob directly and a fake photon sequence to Charlie. Certainly, she should intercept the photon sequence which Zach sends to Bob. With their controller's operation information, during the eavesdropping check Alice can successfully deceive Bob and then obtain his secret message without the permission of the controllers. Bob chooses randomly a controller to publish his or her operation information on each of the sampling photons firstly and then the others do one by one during the eavesdropping check. It ensures each controller can really act as a controller. Suppose Bob let Charlie, Dick, \dots , York publish their operation information firstly and Zach do finally. In other words, Bob does not select randomly a controller to publish his or her information. Alice can then collaborate with Zach to acquire Bob's secret message without the control of other controllers. Alice sends the P -sequence to Zach directly and a fake sequence to Charlie. Zach resends the P -sequence to Bob without doing any operation. Zach can know what operation information he should publish according to the operation information of the controllers Charlie, Dick, \dots , York. The attack of Alice and Zach will not be detected by Bob during the eavesdropping check. On the basis of the above analysis, the present MCQSDC scheme is secure.

So far we have presented a QSDC scheme and a MCQSDC scheme using single photons. Quantum no-cloning theory and the secret transmitting order of photons ensure the security of these schemes. In these schemes, all of the polarized photons are used to transmit the sender's secret message directly to the receiver except those chosen for checking eavesdropping. During the process of the scheme, it only needs once eavesdropping check. Compared with the schemes using entangled state, these schemes are practical within the present technology.

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